

A hydrodynamical model for the FERMI-LAT γ -ray light curve of Blazar PKS 1510-089

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ABSTRACT

A physical description of the formation and propagation of the working surface inside the relativistic jet of the Blazar PKS 1510-089 is used to model its γ -ray variability light curve using *FERMI-LAT* data from 2008 to 2012. The physical model is based on conservation laws of mass and momentum at the working surface as explained by Mendoza et al. (2009). The hydrodynamical description of the working surface is parametrised by the initial velocity and mass injection rate at the base of the jet. We show that periodic variations on the injected velocity profiles are able to account for the observed luminosity. With this, we are able to obtain mass ejection rates of the central engine which are injected at the base of the jet, and oscillation frequencies of the flow, amongst other physical parameters.

Key words: Blazars – PKS 1510-089 – Relativistic Jets – Relativistic Hydrodynamics

1 INTRODUCTION

The study of the γ -ray emission from relativistic jets in AGN constitute a modern test for high energy jet-physics. Among all types of AGN, Blazars (Blazar class is defined as radio loud sources conformed by the BL Lac objects and the Flat Spectrum Radio Quasars -FSRQ, see e.g. Fossati et al. 1997; Ghisellini et al. 1998, and references therein) represent the most extreme class. They are known to have the most powerful jets (e.g. Lister et al. 2009) and also show a highly variable Spectral Energy Distribution (SED) from the radio to the γ -rays wavelengths (see Abdo et al. 2010; D’Ammando et al. 2011, and references therein). The emission produced by their jets is highly amplified due to Doppler boosting effects. This is because the jet of these sources is aligned very close to the observer’s line of sight.

Among the Blazar population, the FSRQ PKS 1510-089 is known to be one of the most powerful objects. Its historical behaviour shows that it is a highly variable object, reaching variations as large as ~ 6 mag in the optical B-band. (see e.g. Liller & Liller 1975). In the optical, a quasar monitoring study done by Lu (1972) presents the first optical light curve of this object. Later, PKS 1510-089 was classified as a high polarised quasar by Moore & Stockman (1981). One of the first radio observations done to this ob-

ject, at sub-arcseconds resolution, revealed a clear structure of knots in the jet (see O’Dea et al. 1988). These authors also find that the observed hot spots had velocities $\sim 0.93c$. Recently, it has been found that PKS 1510-089 has a highly collimated relativistic jet with apparent superluminal speeds going from $20c$ to $46c$ and with a semi-angle aperture for the jet of $\sim 0.2^\circ$ (Jorstad et al. 2005). Since the angle between the relativistic jet and the observer’s line of sight is $1.4^\circ - 3^\circ$, the jet almost coincides with the observer’s line of sight (Homan et al. 2002; Marscher et al. 2010).

PKS 1510-089 was one of the γ -ray sources detected by EGRET (Hartman et al. 1999). Recently, it began to be monitored at high energies with *AGILE* (see e.g. Pucella et al. 2008; D’Ammando et al. 2008) and later also by *FERMI-LAT* and *AGILE* (Tramacere 2008; Ciprini & Corbel 2009; D’Ammando et al. 2009). It has also been studied with *MAGIC* and HESS (Cortina 2012; Wagner et al. 2010). The most prominent outbursts displayed by PKS 1510-089 were observed in 2008 (Kataoka et al. 2008), 2009 (Ciprini & Corbel 2009) and the most recent in 2011 (see Orienti et al. 2012). Therefore, the high activity observed in this source, turns it into an ideal target for the physical study of its highly relativistic jet.

Precise models for the light curve produced by the outburst and flares from Blazars are not done using directly the data variations observed in different wavelengths. Instead, models are applied to explain the behaviour of the Spectral Energy Distribution (SED) (e.g. Abdo et al. 2010; D’Ammando et al. 2011). Direct understanding of the light curve requires a precise knowledge of the hydrodynamical

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behaviour of the relativistic flow. Mendoza et al. (2009) have constructed a hydrodynamical model of the motion of a working surface inside a relativistic jet which is able to fit the observed light curves of long Gamma-Ray Bursts (lGRB's). Since the jets in Blazars are highly relativistic and their jet is nearly pointing towards the observer, similar to the jets observed in lGRB's, the physical ingredients of both phenomena can be considered the same but occurring at different physical scales of energy, sizes, masses, accretion rates, etc. (cf. Mirabel & Rodriguez 2002).

The Blazar PKS 1510-089 is of tremendous importance since it exhibits extreme relativistic motions. As such, its energy curve must present luminosity variations and periods of extreme activity displayed as outbursts that, when physically modelled, can yield a better understanding of the physical parameters associated to the mechanism producing the observed luminosity.

In this letter, we assume that the mechanism producing the observed light curve in the lGRB is exactly the same that produces the variable light curve of the Blazar PKS 1510-089. We thus apply the hydrodynamical jet model presented in Mendoza et al. (2009) to the light curve variations displayed by the Blazar PKS 1510-089 in the γ -ray domain, through observations done with the *FERMI-LAT* telescope.

The letter is organised as follows. In Section 2 we explain in general terms the data reduction process. In Section 3 we describe the characteristics of our hydrodynamic model. The fit done to the data with the hydrodynamic model is explained in Section 4. The results of our fits and the discussion of the main physical parameters obtained in the modelling are presented in Section 5. Throughout this paper we use a standard cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$ and $\Omega_\lambda = 0.73$ (see e.g. Kataoka et al. 2008, and references therein).

2 FERMI-LAT DATA

The gamma-ray fluxes were obtained in the range of 0.2 to 300 GeV using the public database of *FERMI-LAT* from 2008 August 08 to 2012 May 28. The data were reduced with the *FERMI* science tool package (see e.g. Atwood et al. 2009) in the same energy range, taking into account the diffuse galactic background radiation, the instrument response matrix p7v6, and considering a zenith angle $< 105^\circ$. We also calculated the active time of the detector and the PSF. The γ -ray light curve (LC) was constructed modelling the flux with a power law of the form $dN/dE = N_0(E/E_0)^\gamma$. The fluxes and errors obtained with this package are given in photons $\times \text{cm}^{-2} \text{ s}^{-1}$. For further physical interpretation of the data, we have converted these fluxes and errors to $\text{MeV cm}^{-2} \text{ s}^{-1}$.

The photons considered for analysis were taken from a region centred on the coordinates of PKS 1510-089 with a radius of 15° . Figure 1 shows the γ -ray LC, with a bin size of 1 day. We chose these bins, since the errors are larger using shorter bin sizes, complicating the analysis of the data and because particular outbursts can be adequately resolved.

From Figure 1 it follows that the source displayed the historical maximum outburst in MJD 55851, corresponding to 2011 October 17 and reported by Hungwe et al. (2011). Another important outburst occurred in MJD

54899 (2009 March 9) and was observed with *AGILE* (D'Ammando et al. 2009). Several flares or outbursts can be observed in the LC. The most relevant events occurred in MJD 54717 (2008 September 8), MJD 54843 (2009 January 12), MJD 55200 (2010 January 4, Benítez et al. 2011), MJD 55730 (2011 June 18), and MJD 55954 (2012 January 28). This last event was also observed by *AGILE* (Verrecchia et al. 2012) and *MAGIC* (Cortina 2012). Note that Marscher et al. (2010) reports extra flares $< 200 \text{ MeV}$ during the period 54850 - 54950 MJD, which are not seen in our $> 200 \text{ MeV}$ selection.

3 A HYDRODYNAMICAL MODEL FOR THE LIGHT CURVE OF PKS 1510-089

The formation of internal shock waves on a relativistic jet are commonly explained by different mechanisms, such as the interaction of the jet with inhomogeneities of the surrounding medium, the bending of jets and time fluctuations in the parameters of the ejection (see e.g. Rees & Meszaros 1994; Mendoza & Longair 2002; Jamil et al. 2008; Mendoza et al. 2009). In particular, the model by Mendoza et al. (2009) is a hydrodynamical description that can be applied to shock waves inside relativistic jets. This semi-analytical model describes the formation of a working surface inside a hydrodynamical jet due to periodic variations of the injected flow. When fast flow overtakes slow flow, an initial discontinuity is formed and a working surface (two shock waves separated by a contact discontinuity) is produced. The working surface travels along the jet and radiates away kinetic energy. Mendoza et al. (2009) assumed that the efficiency converting factor is ~ 1 and that it is mostly emitted in the γ -ray band. As explained in Section 1, the Blazar PKS 1510-089 behaves as an scaled typical lGRB and as such, the hypothesis used by Mendoza et al. (2009) can be extended to this particular object. As we will discuss in section 5, this assumption is coherent with the physical properties found from the model. Following Mendoza et al. (2009), we assume that flow is injected at the base of the jet with a periodic velocity given by

$$v(\tau) = v_0 + c\eta^2 \sin \omega\tau, \quad (1)$$

where τ is the time in the rest frame of the source, the velocity v_0 is the “average” velocity of the flow inside the jet, and ω is the oscillation frequency. The positive constant parameter η^2 is chosen in such a way that oscillations of the flow are small so that the bulk velocity $v(\tau)$ of the flow does not exceed the velocity of light c . The mass ejection rate $\dot{m}(\tau)$ from the central engine which is injected at the base of the jet is assumed constant through a particular outburst event, but is allowed to vary from one outburst to another. The radiated energy of the flow as a function of time is calculated as the difference between the total energy E_0 injected at the base of the jet and the kinetic energy inside the working surface E_{ws} . The luminosity L is thus calculated as the derivative of this radiated energy with respect to time. Mendoza et al. (2009) showed two ways of calculating this luminosity curve. The first method consisted in a semi-analytical procedure and the second is performed with a full hydrodynamical numerical model. The authors showed that the semi-analytical model is in good agreement with the full

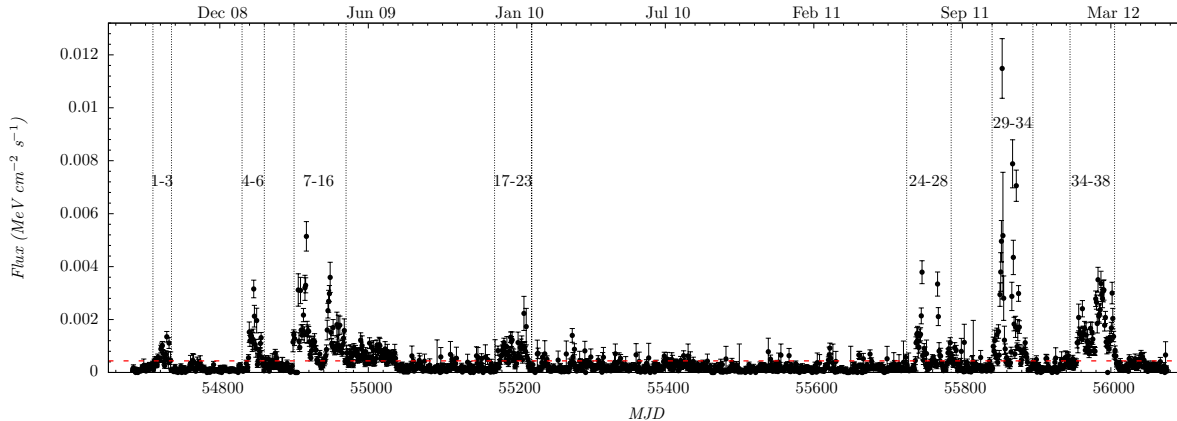


Figure 1. Fermi-LAT light curve of Blazar PKS 1510-089 (from 0.2 to 300 GeV) obtained from 2008 August to 2012 May. The outburst identification number (ID#) labelled in the figure stands for the different flares selected in our work (see text). The 3σ noise level is represented by the red horizontal dashed line.

numerical simulation, and as such we model the light curve of PKS 1510-089 using their semi-analytical approach.

The semi-analytical approach is based on the assumption that equation (1) is valid and as such, one needs to know (or find through fits to observational data) the values of v_0 , η^2 , ω and \dot{m} . Furthermore, in the model, the mass ejection rate \dot{m} enters in the description of the problem since the luminosity $L \propto \dot{m}c^2$. The value of v_0 can be safely taken as the average velocity of the flow of the jet, which must come from observational data (for this particular source D’Ammando et al. 2008, reports a value $\Gamma(v_0) = 18$). Since the value of η^2 has to be small, one starts with a value of η^2 such that the bulk velocity of the flow $v \sim 0.1 \times v_0$ and one allows it to vary in such a way that the Lorentz factor $\Gamma(v)$ of the full velocity v never exceeds the upper limit of ~ 200 , according to the standard expectations of an very large upper limit for the Lorentz factor associated with Blazars (see e.g. Lister et al. 2009). With this, the model is left with three parameters (η^2 , \dot{m} , ω) that fit the observed features in the light curve.

4 MODELLING THE γ -RAY LIGHT CURVE

To model the LC of Figure 1, we have selected the most conspicuous flares and outbursts. The criterion used consists of selecting only those flares or outbursts that are beyond 3σ noise level according to the errors shown in the LC. By doing so, it turns out that 38 relevant peaks were chosen for our fitting.

As explained in section 3, the model has four free parameters. The velocity parameter v_0 is fitted by assuming an average bulk velocity for the jet such that its Lorentz factor is $\Gamma(v_0) = 18$ according to the observations of D’Ammando et al. (2011). For a given outburst, we obtain the parameters \dot{m} and w by doing a linear regression analysis on the data using the model of Section 3, since according to Mendoza et al. (2009), $L \propto \dot{m}c^2$ and $t \propto w^{-1}$. The exact value of η^2 is obtained by trial and error until the best fit (to within 10% of accuracy in ω and \dot{m}) is obtained. To calculate the Flux F we divide the obtained Luminosity L by $4\pi D_L^2$, where D_L is the luminosity distance, which for

this particular case is $D_L = 1919$ Mpc. The results of these fits are shown in Figure 2. The obtained values of the physical parameters of the model for any particular outburst are presented in Table 1.

There are a certain subclass of outbursts that we do not model. These outbursts, labelled 8, 10, 20, 27 and 32 in Figure 1, do not have enough data to allow us an accurate modelling. The outburst labelled 11 seems to have a fall that develops into a constant value before reaching an expected minimum and no data points further, so it seems incomplete. The outbursts 34 and 35 have large errors which also makes the modelling not accurate.

5 DISCUSSION

Table 1 shows the results of the fitting performed on 29 outbursts of the LC of PKS 1510-089. The obtained values of the parameter η^2 are chosen in such a way that the errors in ω and \dot{m} do not exceed 10%. We have also included the maximum and minimum Lorentz factors, Γ_{\max} and Γ_{\min} , obtained for the bulk velocity of the flow.

We have modelled the Light Curve of Blazar PKS 1510-089 for almost 4 years using the hydrodynamical model of Mendoza et al. (2009). The modelling was performed by assuming a periodic velocity injection mechanism at the base of the relativistic jet that leads to the formation of a working surface and is capable of losing energy as it travels along the jet. As explained in section 3, the model by Mendoza et al. was constructed to deal with light curves of IGRB. However, the Blazar PKS 1510-089 has many physical characteristics to be considered a geometrical large scaled version of a IGRB since it has a highly relativistic jet that points towards the observer. In fact, the results presented in Section 5 and Table 1 are in good agreement with the expectations of the physical values that a Blazar jet can have, except for a few large (> 150) bulk Lorentz factors founded for peaks 13, 16, 25, 27 and 30. These somewhat large Lorentz factors in the velocity oscillation show another close similarity with IGRB’s.

The resolution of one day in the *FERMI-LAT* data allowed us to study in great detail the outbursts of PKS

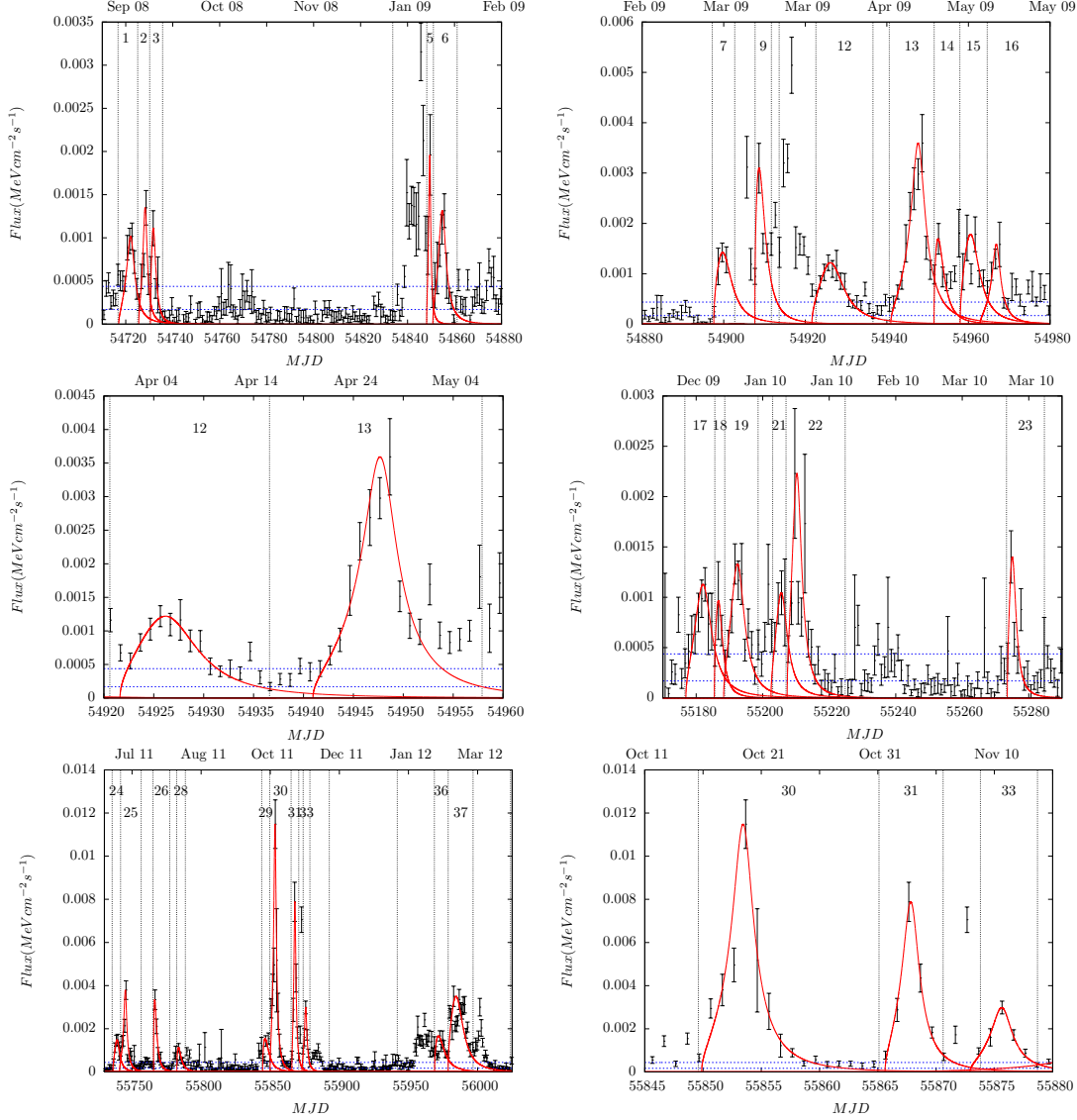


Figure 2. In each panel, the continuous red curve represents the fitting done to the light curve of PKS 1500-089 with the semi-analytical model of internal shock waves (working surfaces) by Mendoza et al. (2009). Blue horizontal dotted-lines in all panels show the 1σ and 3σ noise levels. Top-left panel shows variations from 2008 September to 2009 February. Top-right shows variations from 2009 March to 2009 May, where a couple of large outburst occurred. At the end of these events, a more quiescent state was observed, although a series of successive small flares can be identified. Central left-panel shows a zoom of the peaks 12 and 13. Central right-panel shows the variations observed from 2009 December to 2010 March. Bottom left-panel shows recent variations occurred from 2011 July to 2012 March. Finally, bottom-right panel shows a zoom of the October 2011 outburst. This outburst is \sim three times more luminous than the previously one observed in 2009 March. Up to now, this is the most violent outburst observed in the γ -ray waveband by *FERMI*.

1510-089. Some of the outbursts reported in this letter, corresponding to early 2012, were also reported by *AGILE* (Lucarelli et al. 2012) and *MAGIC* (Cortina 2012).

The range of parameters as presented in Table 1, i.e. $\dot{m} \sim 10^{-7} - 10^{-10} M_{\odot} \text{yr}^{-1}$, $\omega^{-1} \sim 20 - 70$ min and variations of the Lorentz factor Γ between 20–180, denote a scaling between the IGRB counterparts found in Mendoza et al. (2009) for which $\dot{m} \sim 10^{-1} - 10^{-2} M_{\odot} \text{s}^{-1}$, $\omega^{-1} \sim 10$ s and $\Gamma \sim 50 - 500$. The inferred high relativistic Lorentz factors associated to the motion of the bulk velocity of the flow inside the jet of PKS 1510-089 makes it an ideal candidate for the application of the hydrodynamical model of Mendoza et al. (2009). This is why that physical model can

be applied naturally to IGRB and in this particular case to the extreme relativistic motion of the jet in the Blazar PKS 1510-089. The variations of the injected flow at the base of the jet cause the formation of working surfaces that produce flares or bursts of γ -rays in the structure of the jet. The physical mechanism producing the oscillations of the input flow, which allows fast fluid to overtake the slow one, leading to the formation of working surfaces, is beyond the scope of this letter. However, steady flow deviations and oscillations in such complicated phenomena are expected since the accretion-ejection mechanism associated to a particular object is not necessarily expected to be of constant velocity and mass accretion-ejection rates.

Period	ID #	MJD +54000	η^2/c	Γ_{max}	Γ_{min}	ω^{-1} (day)	$\dot{m} 10^{-9}$ ($M_{\odot} \text{yr}^{-1}$)
08 Sep	1	722	0.00152	143.14	12.78	0.0142	1.26
08 Sep	2	728	0.00152	143.14	12.78	0.0076	2.22
08 Sep	3	731	0.00138	55.15	13.08	0.0041	6.71
09 Jan	5	849	0.00152	143.14	12.78	0.0036	4.69
09 Jan	6	855	0.00151	120.55	12.8	0.0115	2.67
09 Mar	7	899	0.00135	50.71	13.15	0.0077	13.1
09 Mar	9	908	0.00119	37.56	13.53	0.0061	128
09 Apr	12	925	0.00144	69.2	12.95	0.0015	5.36
09 Apr	13	948	0.00153	186.32	12.76	0.0186	11.2
09 May	14	952	0.00121	38.67	13.48	0.0041	35.2
09 May	15	957	0.00140	58.84	13.04	0.0086	15.5
09 May	16	967	0.00153	186.32	12.76	0.0110	2.17
09 Dic	17	1182	0.00149	95.86	12.84	0.0015	2.73
09 Dic	18	1186	0.00136	52.07	13.13	0.0044	5.71
09 Dic	19	1191	0.00149	95.86	12.84	0.0124	3.81
10 Jan	21	1205	0.00147	81.97	12.88	0.0095	2.98
10 Jan	22	1209	0.00149	95.86	12.84	0.0086	10.7
10 Mar	23	1274	0.00143	66.11	12.97	0.0049	7.65
11 Jun	24	1739	0.00146	76.96	12.76	0.0092	6.65
11 Jul	25	1745	0.00153	186.32	12.76	0.0115	12.4
11 Jul	26	1766	0.00110	33.54	13.75	0.0034	212
11 Aug	28	1783	0.00110	33.54	13.75	0.0048	24.2
11 Oct	29	1848	0.00117	36.54	13.58	0.0072	34.5
11 Oct	30	1853	0.00153	186.32	12.76	0.0098	51.4
11 Nov	31	1867	0.00152	143.14	12.78	0.0062	75.9
11 Nov	33	1875	0.00152	143.14	12.78	0.0077	10.9
12 Feb	36	1972	0.00117	36.54	13.58	0.0113	40.1
12 Mar	37	1982	0.00139	56.90	13.06	0.0196	62.8

Table 1. Different physical quantities obtained for the outbursts modelled in this work. The mean Lorentz factor of the bulk velocity of the flow was assumed to be 18. The first three columns from left to right are the period, numeric identification of the outburst (ID #) and the date corresponding to the maximum luminosity for a particular outburst. Columns four and seven are the obtained values for the parameters η^2 (measured in units of the speed of light c) and the inverse frequency ω^{-1} relevant to the particular variational model of equation (1). The errors associated with these parameters have an accuracy of 10%. Column eight represents the mass injection rate \dot{m} of the flow at the base of the jet. Columns five and six correspond to the minimum and maximum values of the Lorentz factor of the bulk flow for each particular outburst.

It is important to note that the assumption of seeing a Blazar as a scaled version of a IGRB is not new. In an early attempt for finding a unified model of jet and central-engine power, Mirabel & Rodriguez (2002) made this identification. The more relativistic a Blazar jet is, the more it will resemble a IGRB. The idea of having a unified physical model for all types of astrophysical jets was first suggested by the pioneering works for the astrophysical scaling laws of black holes by Sams et al. (1996) and Rees (1998). The work presented in this letter further strengthens arguments about a unified picture of all astrophysical relativistic jets.

PKS 1510-089 resulted to be an ideal target to test the model by Mendoza et al. (2009) since it closely resembles a IGRB in some of its outbursts. Future tests of the model have to be done with a wide variety of Light Curves from a large collection of Blazars and micro-quasars.

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